

# SURFACE HEAT BUDGET OF THE PAMPA DE LA JOYA, PERU

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## ABSTRACT

The surface heat budget for the absolutely dry soil of the Pampa de La Joya, Peru, a portion of the Atacama Desert, was determined for three round-the-clock periods in July 1964. The diurnal variations are described by the mean value and the amplitude and phase angle of the first three harmonics. The measurements include global insolation, net radiation, soil heat flux density, sensible heat flux density, surface temperature, and air temperature at 20, 40, 80, 160, and 320 cm. The instruments used are described, and an estimate of the errors in measurement is made for each.

## 1. INTRODUCTION

During July 1964, a micrometeorological field program in the Pampa de La Joya, Peru, was inaugurated by H. H. Lettau and supported by the Center for Climatic Research, Department of Meteorology, The University of Wisconsin. The primary purpose of the expedition was to study the dynamics of the air flow which causes the migration of the crescentic sand dunes, commonly called barchans, present on the Pampa de La Joya. Finkel (1959), Hastenrath (1967), and H. and K. Lettau (1969) have described the barchans in detail. Lettau (1968) has discussed certain aspects of the local circulation and dune migration.

The West Coast of South America, about 5° S. to 30° S. latitude between the Pacific Ocean and the Andes Mountains, is the Atacama Desert, one of the world's most arid regions. La Joya is located at 16°44' S. latitude and 71°51' W. longitude between Mollendo and Arequipa as shown in figure 1. The area shown in figure 2 is part of the Pampa de La Joya indicating the barchan field and the location of the barchan "Finkel 26" which was the camp site for the expedition. The character of the desert area where the measurements were made may be seen in figure 3.

The purpose of this paper is to analyze the diurnal variation of heat budget constituents and related measurements in an absolutely dry climate, and thus to increase the available surface heat budget data in a meteorologically neglected but interesting area.

## 2. THEORY OF THE SURFACE HEAT BUDGET

The heat budget at the air-soil interface may be represented by the equation

$$R_0 = S_0 + Q_0 + E_0 + P_0 \quad (1)$$

where  $R_0$  is the net radiative heat flux density (ly/min),  $S_0$  the soil heat flux density,  $Q_0$  the sensible heat flux density to the air,  $E_0$  the latent heat flux density to the air, and  $P_0$  the heat flux density required for photochemical reactions. The subscript 0 refers to the surface.

The lack of soil moisture, rainfall, and condensation on the Pampa de La Joya, apparent in the absence of plant growth, allows the assumption that  $P_0 = 0$  and  $E_0 = 0$ . The heat budget equation then reduces to the extreme desert-type heat budget in the form

$$R_0 = S_0 + Q_0. \quad (2)$$

The three terms are generally positive during the daytime and negative during nighttime.

The sensible heat flux density to the air may be related to the gradient of potential temperature  $\theta'$  and an eddy

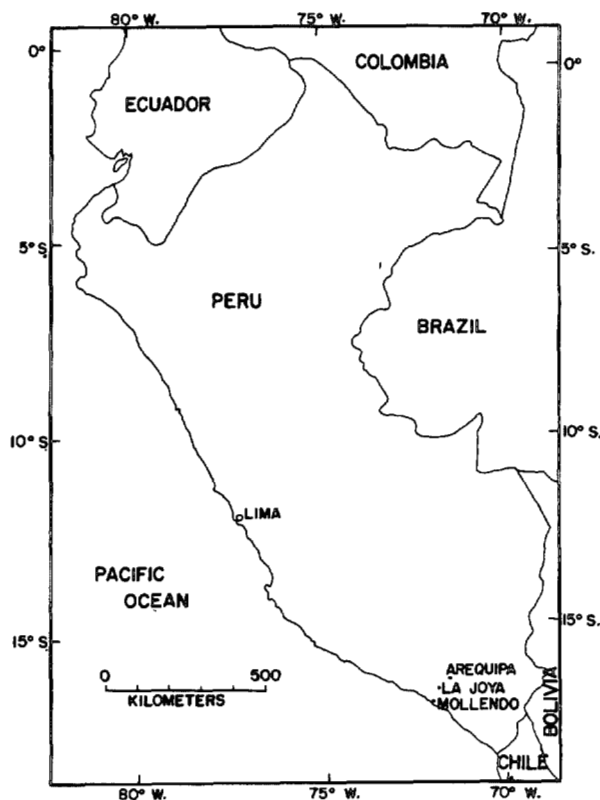


FIGURE 1.—Map of Peru indicating the location of Arequipa, La Joya, and Mollendo.

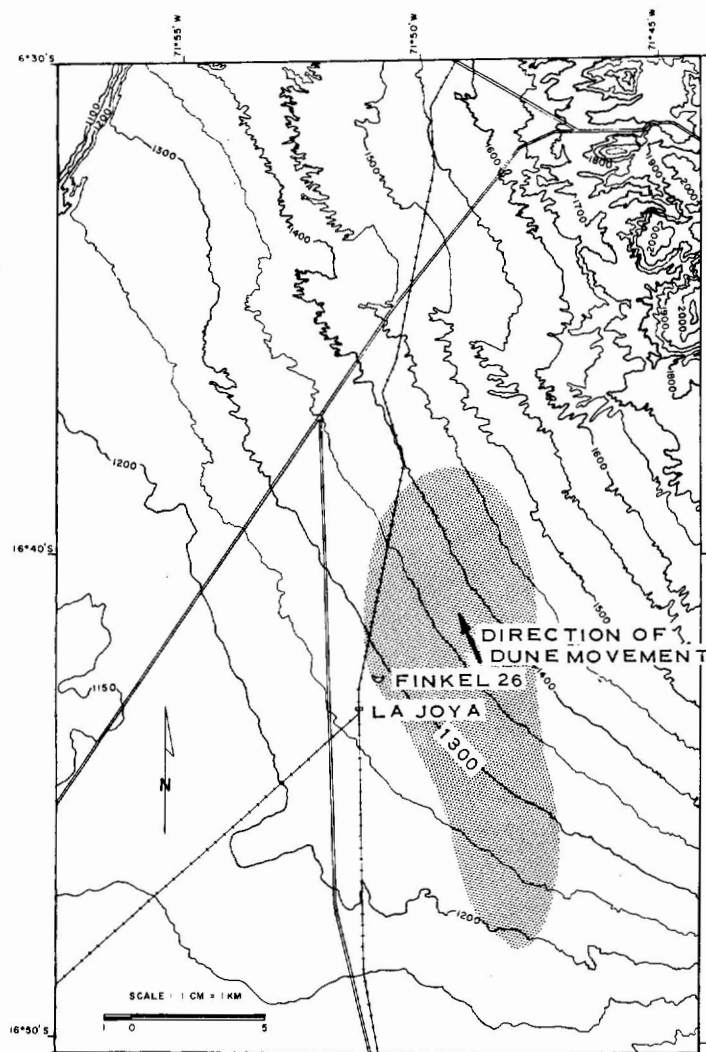


FIGURE 2.—Topographic map of the Pampa de La Joya, Peru. The shaded area indicates the barchan field and the location of the barchan Finkel 26 near which the heat budget measurements were made.

diffusivity for heat  $K_h$  in the following form:

$$Q_0 = -\rho C_p K_h \theta' \quad (3)$$

where  $\rho$  is the air density ( $\text{gm cm}^{-3}$ ),  $C_p$  the specific heat per unit mass for air ( $\text{cal gm}^{-1}(\text{°K})^{-1}$ ),  $K_h$  the eddy diffusivity for heat ( $\text{cm}^2 \text{sec}^{-1}$ ) and  $\theta'$  the vertical potential temperature gradient in the air ( $\text{°K cm}^{-1}$ ). The assumptions made are that the flux of sensible heat is directly proportional to the potential temperature gradient in the air, and that there is no divergence of sensible heat in and below the air layer where the potential temperature gradient is measured.

### 3. MEASUREMENTS AND INSTRUMENTATION

The micrometeorological measurements made on the Pampa de La Joya, Peru, included the soil heat flux



FIGURE 3.—Barchan in the area of Finkel 26 (see fig. 2) showing the general character of the desert surface.

density at  $-0.5$  cm, extrapolated surface temperature at  $-0.1$  cm, net radiation, and air temperature at five levels. A detailed description of the measurements system is given by Stearns (1967).

The soil heat flux density was measured by a microscope slide "flux plate" with 100 thermocouple junctions across the plate. The flux plate was calibrated in situ by the soil temperature integral method assuming a volumetric heat capacity of  $0.286 \text{ cal cm}^{-3}(\text{°C})^{-1}$  for the desert sand (Stearns, 1969).

Net radiation (fig. 4) was measured by a modified Suomi-Kuhn shielded net radiometer (Suomi, 1958) and a ventilated net radiometer (Suomi, 1954). The ventilated radiometer was calibrated by shading, against an Eppley pyranometer, but the ventilated radiometer was not operating properly prior to July 12, 1964, so only the shielded radiometer data were available from July 8 to July 12, 1964. Figure 5 is a comparison between the two radiometers. For the heat budget calculations, the shielded radiometer was corrected to the ventilated radiometer according to figure 5 in order to have radiation data for the period July 8 to July 12, 1964 (Stearns, 1967).

An estimate of the soil surface temperature was made by extrapolating the  $-0.5$ ,  $-2.0$ , and  $-5.0$  cm temperature to  $-0.1$  cm using the Lagrangian method of fitting a parabola through three points in order to predict the fourth. The actual equation used was

$$T_{-0.1} = 1.48 T_{-0.5} - 0.555 T_{-2.0} + 0.74 T_{-5.0} \quad (4)$$

where  $T$  is temperature ( $\text{°C}$ ) and the subscript indicates the depth of the temperature used or estimated. Commencing July 12, 1964, an independent estimate of the soil surface temperature was obtained by a nickel-wire resistance thermometer resting on the soil surface. A comparison between the resistance thermometer temperature and the extrapolated soil temperature is shown in figure 6.

When the surface temperature was changing rapidly, the extrapolated surface temperature lagged about  $2^{\circ}\text{C}$  behind the resistance thermometer temperature (Stearns, 1967).

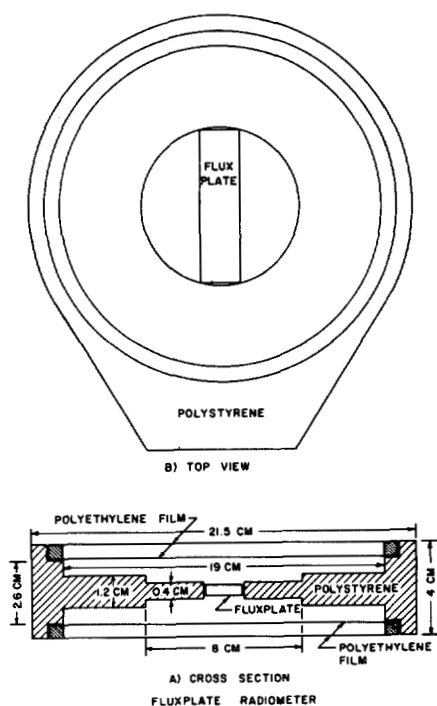


FIGURE 4.—Construction details of the shielded radiometer used for measuring net radiation on the Pampa de La Joya, Peru. The radiation detector is a blackened flux plate with two layers of 0.5 mil polyethylene film on each side to shield the flux plate from ventilation.

The air temperature profile differences were measured by 10 junction thermopiles between height intervals of 20 to 40, 40 to 80, 80 to 160, and 160 to 320 cm. The thermopiles were ventilated at about  $5 \text{ m sec}^{-1}$  and shielded from solar radiation. The absolute reference temperature was measured by a 1N-2326 diode thermometer checked occasionally during recording against a mercury-in-glass thermometer (Stearns, 1967).

The data were recorded at 1-min intervals on a 24-point Honeywell Electronic Recorder of 0- to 2.5-mv range, read from the charts directly to punch cards by a chart reader and then processed by electronic computer.

#### 4. RESULTS

The data yielded estimates of  $R_0$  and  $S_0$  at 1-min intervals with  $Q_0$  determined from equation (2) as  $Q_0 = R_0 - S_0$ . Figure 7 presents a diurnal cycle of 10-min mean values of  $R_0$ ,  $S_0$ , and  $Q_0$ . The slight dip in  $S_0$  and increase in  $Q_0$ , at about 1200 EST on July 11, 1964, was associated with a sharp increase in the wind speed at 320 cm from about  $400 \text{ cm sec}^{-1}$  to  $700 \text{ cm sec}^{-1}$  as shown in figure 8. The decrease in soil surface temperature and increase in the 20-cm air temperature at the same time may be seen in figure 9. The sky remained free of clouds.

The air temperature at five levels, heat budget, and surface temperature were analyzed harmonically and the results are given in table 1 for three diurnal periods on the Pampa de La Joya, Peru. Periods were selected so that the available data were nearly continuous with some

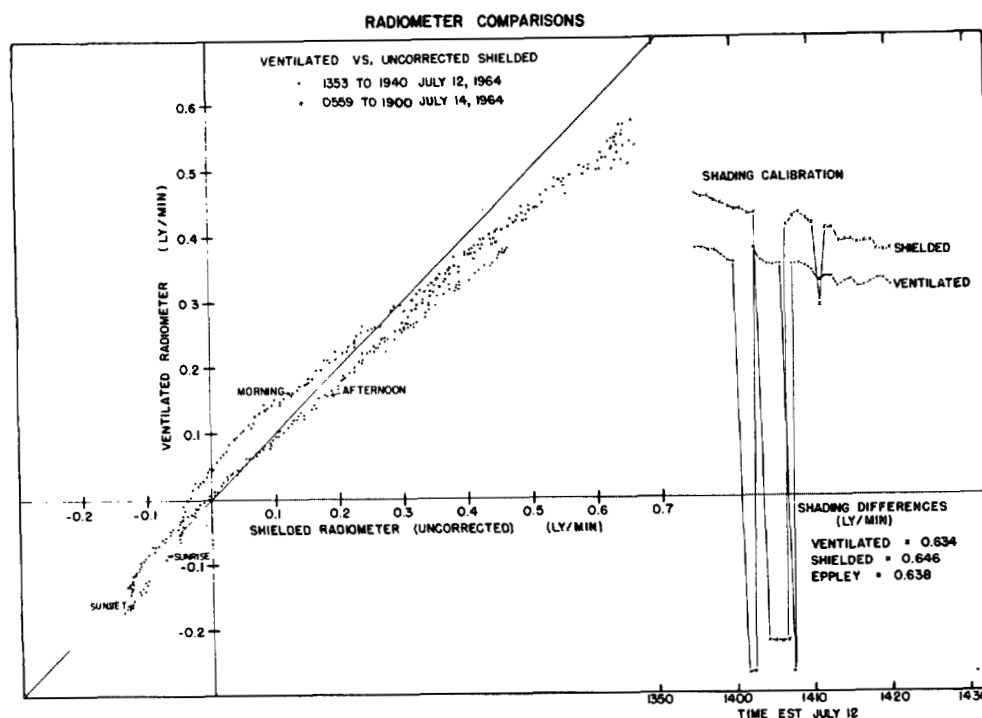


FIGURE 5.—Comparison between the ventilated net radiometer and the uncorrected shielded radiometer and a shading calibration of the two instruments. The calibration factor for the ventilated radiometer was the mean obtained from several shadings using an Eppler pyranometer as the radiation standard.

interpolation necessary during the nighttime. The differences between the three diurnal periods for the mean values and the amplitudes and phase angles of the first and second harmonics are negligible.

An examination of the diurnal period means of the air temperature profile reveals a minimum value at about 80 to 100 cm. Figure 10 illustrates 6-hr mean potential air temperatures and potential air temperature gradients

for July 11, 1964, where the 6-hr means are taken over periods of time that are clearly lapse or inversion. The presence of the minimum in the mean diurnal potential air temperature profile is a good illustration of the difficulties that would arise by applying equation (3) to diurnal periods where the potential temperature gradient is determined at some distance from the surface. Figure 10 shows that, as one approaches the surface, the eddy diffusivity for heat approaches a value nearly constant for the diurnal period at about  $400 \text{ cm}^2 \text{ sec}^{-1}$  at a height of 28.2 cm. Equation (3) could then be applied to the mean diurnal gradient of potential air temperature, but only at a height where it is already known that the eddy diffusivity for heat is constant during the diurnal period.

## 5. ACCURACY

The use of only one set of instruments makes it difficult to estimate the accuracy of the measurements. Figure 4 shows that the two net radiation instruments were not in the same plane, and it could be that neither instrument was truly horizontal. The use of an Eppley pyranometer as the radiation standard immediately introduces an uncertainty of  $\pm 5$  percent in the calibration of the instrument. The cosine response of the pyranometer is poor at sun elevation angles of less than  $30^\circ$ , so calibrations of the net radiometers were done within 2 hr of solar noon. The pyranometer, ventilated net radiometer, and shielded net radiometer were shaded from the solar beam at nearly the same time, as seen in figure 5, with the value of the solar beam determined by the pyranometer. The net radiation is thus probably known to  $\pm 5$  percent with an uncertainty of  $\pm 0.02 \text{ ly min}^{-1}$  in the zero point

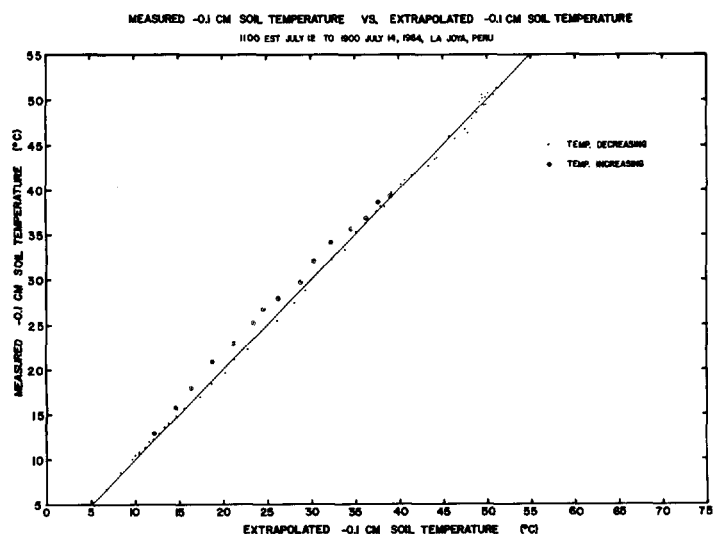


FIGURE 6.—Ten-minute mean soil temperature at the nominal depth of  $-0.1 \text{ cm}$  as measured by an  $0.001 \text{ mil}$  nickel-wire resistance thermometer versus the temperature determined by the extrapolation of  $1\text{-min}$  subsoil temperatures to  $-0.1 \text{ cm}$  and then averaged for  $10\text{-min}$  periods. Allowance was not made for phase lags in the extrapolated subsoil temperatures.

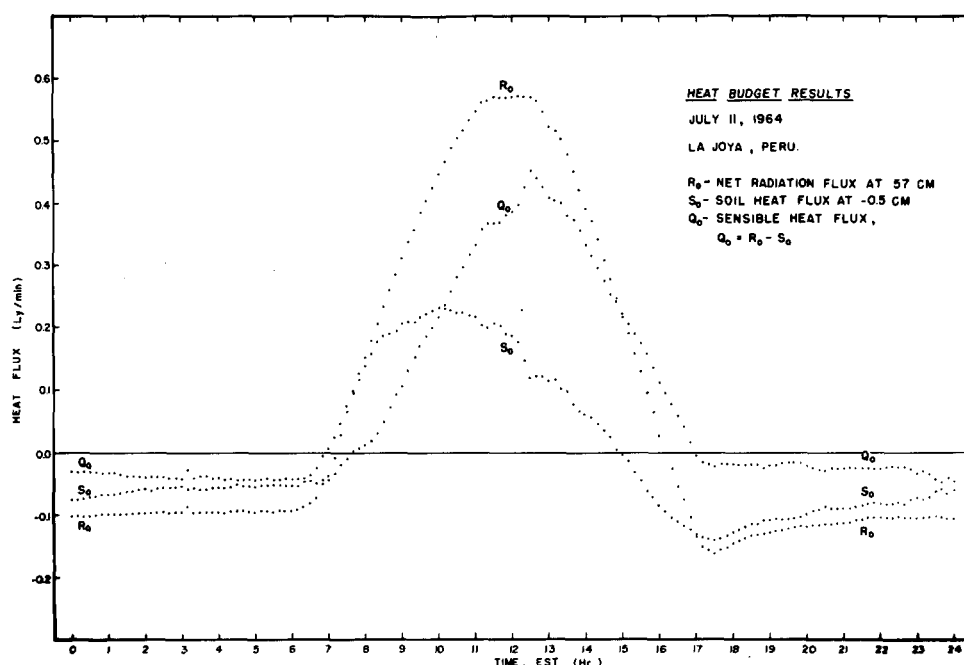


FIGURE 7.—The heat budget on the Pampa de La Joya, Peru, for the diurnal period of July 11, 1964.

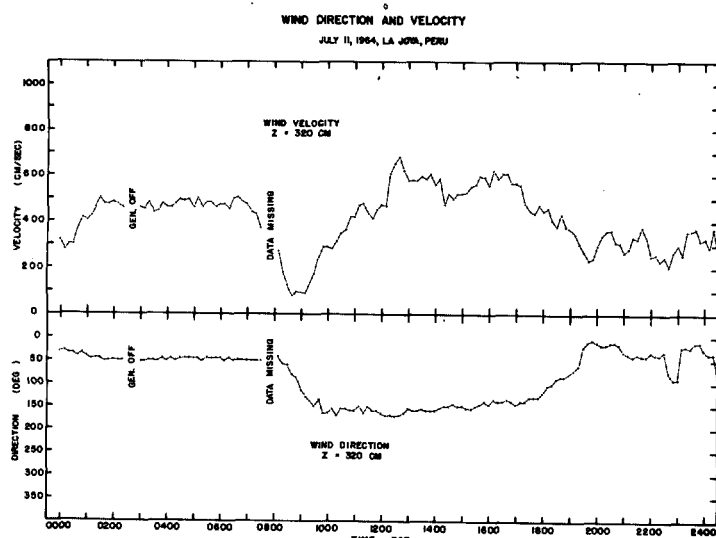


FIGURE 8.—Wind direction and speed at 320-cm height above the surface of the Pampa de La Joya, Peru. The increase in wind speed at 1200 EST was associated with an increase in  $Q_0$  and a drop in surface temperature at the same time.

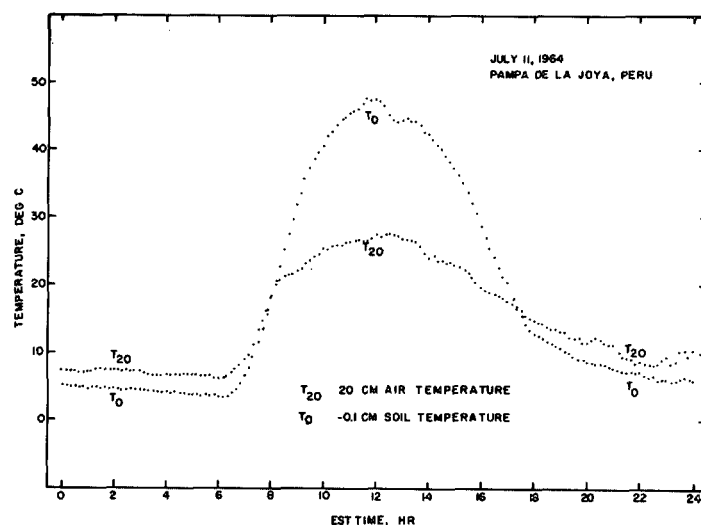


FIGURE 9.—Soil temperature at  $-0.1$  cm estimated by extrapolation from below and the 20-cm air temperature for the diurnal period of July 11, 1964, on the Pampa de La Joya, Peru. The drop in the  $-0.1$ -cm soil temperature at 1200 EST is associated with an increase in wind speed.

TABLE 1.—The results of the harmonic analysis of data collected during three diurnal periods on the Pampa de La Joya, Peru, during July 1964. The harmonic analysis was done on 144 points for the diurnal period, each consisting of the mean value of 10, 1-min samples. The first three harmonics represented more than 98 percent of the variance in the data. The sensible heat flux density  $Q_0$  is determined as  $R_0 - S_0$ , and the surface temperature  $T_0$  is not the radiative temperature of the desert surface. Phase is given in radians and the data may be reconstructed, for example, by the series  $A(t) = A_0 + \sum_{n=1}^3 A_n \cos(\omega t - \alpha_n)$  where  $A(t)$  is the value at time  $t$  in hours from local midnight,  $A_0$  is the mean value for the diurnal period,  $A_n$  is the amplitude of the  $n$ th harmonic,  $\omega = 2\pi/24$  is the angular velocity (radians/hr), and  $\alpha_n$  is the phase angle of the  $n$ th harmonic in radians

	Diurnal period	Period mean	First harmonic		Second harmonic		Third harmonic	
			Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
RS Solar radiation (ly min <sup>-1</sup> )	I	0.339	0.560	3.142	0.292	0.099	0.054	2.940
	II	0.339	0.557	3.142	0.289	0.268	0.055	3.044
	III	0.332	0.543	3.142	0.279	0.099	0.053	3.215
R <sub>0</sub> Net radiation (ly min <sup>-1</sup> )	I	0.066	0.303	3.050	0.182	6.235	0.057	3.065
	II	0.069	0.299	3.052	0.179	6.232	0.052	3.220
	III	0.061	0.288	3.055	0.176	6.236	0.053	3.241
S <sub>0</sub> $-0.5$ cm Soil heat flux density (ly min <sup>-1</sup> )	I	0.001	0.139	2.700	0.087	5.857	0.014	2.671
	II	-0.004	0.138	2.658	0.082	5.772	0.019	2.050
	III	0.002	0.140	2.724	0.082	5.839	0.022	2.169
Q <sub>0</sub> Sensible heat flux density (ly min <sup>-1</sup> )	I	0.065	0.175	3.286	0.106	0.320	0.046	3.226
	II	0.073	0.180	3.350	0.112	0.277	0.048	3.595
	III	0.059	0.163	3.337	0.105	0.259	0.047	3.667
T <sub>0</sub> $-0.1$ cm Soil temperature (°C)	I	19.40	20.54	3.462	9.17	0.276	0.78	3.365
	II	18.57	20.53	3.370	8.82	0.153	1.69	2.436
	III	19.67	21.70	3.400	9.55	0.266	1.83	2.874
T <sub>20</sub> 20 cm Air temperature (°C)	I	14.56	8.76	3.675	2.58	3.180	0.96	0.432
	II	14.79	10.69	3.421	3.21	3.100	1.19	1.611
	III	15.39	10.18	3.571	2.62	3.506	1.08	1.020
T <sub>40</sub> 40 cm Air temperature (°C)	I	14.40	8.30	3.695	2.36	3.152	1.03	0.424
	II	14.60	9.54	3.423	2.96	3.060	1.24	1.553
	III	15.29	9.70	3.580	2.42	3.480	1.12	1.035
T <sub>80</sub> 80 cm Air temperature (°C)	I	14.33	7.79	3.714	2.17	3.055	1.09	0.446
	II	14.48	8.92	3.426	2.75	2.990	1.26	1.513
	III	15.27	9.11	3.591	2.23	3.437	1.12	1.028
T <sub>160</sub> 160 cm Air temperature (°C)	I	14.32	7.28	3.744	2.03	3.151	1.09	0.412
	II	14.54	8.30	3.436	2.70	2.910	1.21	1.486
	III	15.44	8.47	3.613	2.20	3.372	1.10	0.990
T <sub>320</sub> 320 cm Air temperature (°C)	I	14.72	6.38	3.775	2.09	3.012	1.09	0.589
	II	15.05	7.16	3.493	2.99	2.800	1.00	1.385
	III	16.16	7.18	3.669	2.45	2.994	1.08	0.820

I, diurnal period beginning 0940 EST on July 9, 1964

II, diurnal period beginning 1800 EST on July 10, 1964

III, diurnal period beginning 1800 EST on July 11, 1964

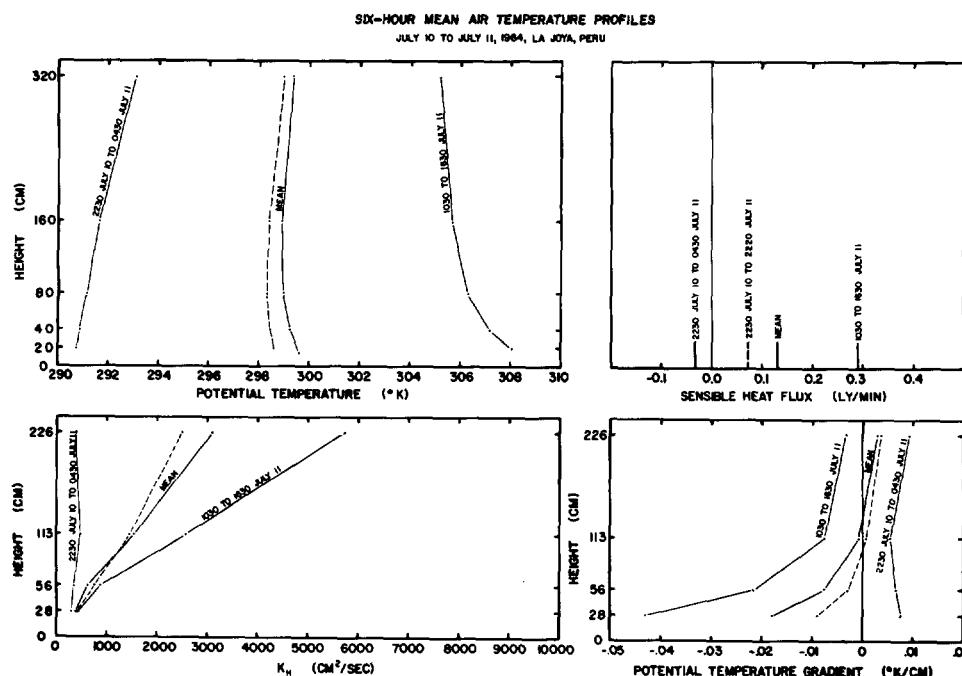


FIGURE 10.—Height profile of potential air temperature, potential air temperature gradient, and eddy diffusivity for heat ( $K_h$ ) for 1030 EST on July 11 to 1030 EST on July 12, 1964, on the Pampa de La Joya, Peru. The dashed lines are for the 24-hr mean which contains the two 6-hr periods of lapse and inversion conditions and "mean" refers to the average of the two 6-hr periods which are clearly lapse or inversion.

based on the value of the sensible heat flux density at the time the potential air temperature gradient was zero. The soil heat flux density error is of the order of  $\pm 4$  percent (Stearns, 1969). The error in the extrapolated  $-0.1$ -cm soil temperature will depend upon the rate at which the soil temperature is changing and at best represents the temperature of the lower part of the sand grains and not the radiative temperature of the sand surface. The error in the zero of the sensible heat flux density is approximately  $\pm 0.02 \text{ ly min}^{-1}$  with an uncertainty, related to the Eppley pyranometer calibration, of  $\pm 5$  percent in the amplitude.

The air temperature gradient was recorded to  $\pm 0.025^\circ\text{C}$ , but the standard deviation of a 10-min sample was often of the order of  $0.1^\circ\text{C}$ . The differences from one level to the next should be within  $\pm 0.025^\circ\text{C}$ , but as to whether this represents the air temperature at the nominal height is open to question. The 80-cm air temperature seems occasionally to be in error relative to 40 and 160 cm, but it was not possible to correct the data; the discrepancy is of the order of  $\pm 0.10^\circ\text{C}$ .

## 6. CONCLUSIONS AND FUTURE PLANS

The excessive dryness and low thermal admittance of the soil (Stearns, 1969) result in relatively extreme sensible heat flux density to the air with peak values of  $0.4 \text{ ly min}^{-1}$ . The small surface roughness of about  $0.02 \text{ cm}$  (Stearns, 1967) contributes to large air-to-surface tem-

perature differences of as much as  $20^\circ\text{C}$ . Large flux densities of sensible heat to the air, coupled with the smooth surface, leads to extremes in the vertical gradients of air temperature and wind speed near the surface. The resulting negatively large Richardson numbers permit conclusions on the ratio of the eddy diffusivity for heat to the eddy diffusivity for momentum and thus on profile structure in the surface layer. These results will be presented in the future.

The reliability of the diurnal wind variation in the surface layers combined with the regularity of the diurnal heat budget and the low surface roughness makes the area ideal for the study of diabatic wind and temperature profile structure in the surface layer.

The Peruvian Government plans to irrigate parts of the Pampa de La Joya. It will be of interest to determine how the heat budget and associated parameters reported above may be changed by the proposed modification of the desert surface.

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